NUMERICAL SIMULATION OF THE INFUSION PROCESSES VALIDATION & PARAMETRIC STUDY

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ABSTRACT: The infusion process has been developed to be a cost-effective technique for the fabrication of large and complex composite structures [1]. Thus, this process has been identified as an alternative to the RTM (Resin Transfer Moulding) as well as the conventional autoclave prepreg technique [2].
In the infusion process, it is important to predict resin infusion time and final thickness of the part according to the process condition such as compaction pressure and resin temperature. Hence, in the present study, we propose a numerical model to simulate the resin infusion through the fibre preform and to predict the resin infusion time. A validation of the numerical resin infusion model is made through the comparison between experimental and numerical results, and a good agreement is observed. Based on this model, a numerical code has been developed to calculate resin infused height for various values of compaction pressure and resin temperature.
In the parametric study, the influence of compaction pressure on the final height of the part is investigated. The infusion time is also studied for the various process conditions.

KEYWORDS: Infusion Process, Hydro-Mechanical Coupling, Infusion Height Percentage, Resin Infusion Time.

INTRODUCTION

The large composite parts are increasingly used particularly in aeronautic industry. The LCM (Liquid Composites Molding) processes are being employed to manufacture high quality and complex-shaped fibre reinforced polymeric composite parts. We can classify them into two groups: the injection by resin transfer (RTM & derivatives) and the infusion by resin infiltration (Infusion & derivatives). In infusion processes, dry textile preforms are infiltrated by semi-cured resin (Fig. 1) and the resin is consolidated and cured in a single step, eliminating the labour to lay-up of prepreg tapes.

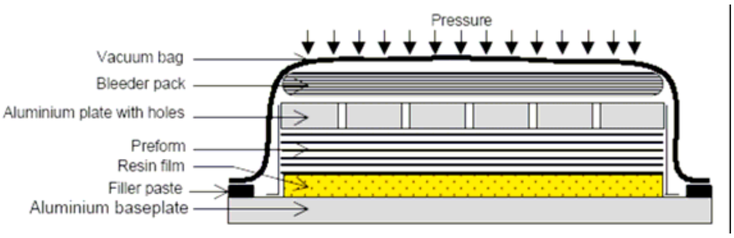

Fig. 1 Resin infusion process setup.

Several investigators have studied and proposed models for the RFI (Resin Film Infusion) process used in composites manufacturing. Resin flow through the dry fibres is conventionally modelled as an unsaturated flow through porous media, where Darcy's law is employed. The determination of the exact location of the flow front is an important issue in the analysis. When high pressure gradients are applied, it is necessary to treat the fibre layers as deformable. A study on this fluid-structure interaction problem has been performed by Ambrosi and Preziosi [3]. Another important issue is the elimination of entrapped air since the presence of voids can significantly degenerate the quality of the composites. A mathematical model of void formation during the RFI process has been developed by Sevostianov et al [4]. In a paper of Blest et al. [5], the modelling and simulation of resin flow, heat transfer and the curing of multilayer thermoset composites by the resin film infusion process has been treated. Loos and MacRae [6] have developed an analytical model for two-dimensional resin film infusion process, which can be used to simulate non-isothermal infiltration of a hot-melt resin into a textile preform of complex shape. A non-isothermal RFI process for stitched stiffened panels was numerically modelled by Han et al [7]. The performance of the stitched stiffened panels under compressive loading has been compared with that of the unstitched stiffened panels. Recently, an analytical formulation of governing equations for flow of incompressible fluid through compacting porous media and their application to vacuum infusion of composite materials was made by Correia et al [8].
The objective of this work is to develop and to verify a comprehensive numerical model for the simulation of the infusion processes, and for the prediction of the final thickness and the resin infusion time. Particularly, the fibre reinforcement is considered as deformable and the resin infiltration is held through the thickness of the preform.

ANALYSIS OF INFUSION PROCESSES

We propose a set of governing equations modified to consider the preform deformation and the resin infiltration at the same time. Then a numerical formulation is employed with the models for the material properties (such as preform and resin).

Governing equations

Hydrological flow in consolidating soil was initially discussed by Biot in 1941 [9]. These theories have been adapted to composites manufacturing by Gebart [10], Gutowski [11, 12]. The basis of all models is the continuity equation (eq. 1), where q is the relative velocity, V_f the fibre volume fraction and u_{si} the solid velocity. The resin flow through the fibre system is a typical example of flow through a porous media, which, on the macroscopic scale, is well described by the Darcy's law (eq. 2) [13] relating linearly the fluid velocity q to the pressure gradient ∇p by the resin viscosity μ and the permeability K_z of porous medium.
As presented in table 1, we represent the whole formulations corresponding to the modelling of Hydro-Mechanical (HM) coupling applied to the infusion process.

Table 1 Equations for the HM coupling analysis

Equations		Dependent variables
Mass balance (eq. 1)	$\nabla \cdot q = \frac{1}{V_f}\left(\frac{\partial V_f}{\partial t} + u_{si}\nabla V_f\right)$	q, V_f
Darcy's law (eq. 2)	$\nabla p = -\frac{\mu}{K_z(V_f)} q$	p
Force balance (eq. 3)	$\nabla \cdot \sigma_z^{'} - \nabla p = 0$	$\sigma_z^{'}$
Constraint-Fibre volume fraction relation (eq. 4)	$\sigma_z^{'} = C_z(V_f)$	None
total :	4 equations	4 variables (scalars)

Experimental device for Hydro-Mechanical coupling

In infusion processes, the fibre volume fraction can change dynamically as the applied pressure is re-distributed between the resin and the preform. Hence, it is important to model the compaction of the fabric and its relation with the fibre volume fraction as a function of the applied pressure. In addition, the permeability of fabric depends on the fibre volume fraction. Thus, it is also of significance to model the relationship between the permeability and fibre volume fraction.
An experimental device with hydro-mechanical coupling HMz was developed [14] and used to obtain and the permeability ($K_z = 2.10^{-13}.V_f^{-3,06}$) and the compressibility of perform ($V_f = 0,483 + 0,123.\sigma_z^{'} - 0,045.\sigma_z^{'\,2} + 0,009.\sigma_z^{'\,3} - 9,3.10^{-4}.\sigma_z^{'\,4} + 3,71.10^{-5}.\sigma_z^{'\,5}$).

Numerical formulation

The numerical algorithm used in this study is based on a one dimensional discretization of the governing equation by the finite difference method with a moving boundary flow front. The pressure and the saturation values are calculated at the nodes. The fibre volume fraction and the permeability are computed and assigned to each element. The combination of equations (1) and (2), gives the following governing equation, expressed in the 1D form:

$$\frac{\partial}{\partial z}\left(-\frac{K_z}{\mu}\frac{\partial P}{\partial z}\right) = \frac{1}{V_f}\frac{\partial V_f}{\partial t} + \frac{1}{V_f}\frac{\partial V_f}{\partial z}v_k^{\,f} \qquad (5)$$

where $v_k^{\,f}$ is solid velocity (fibre velocity) in transverse direction.
The term ($\frac{1}{V_f}\frac{\partial V_f}{\partial z}v_k^{\,f}$) in RHS of the equation (5) represents the relaxation or the compression of the wet fibres. To deal with it, the initial grid of the field is deformed in such a manner to take into account the relieving or the compression of the porous environment [15, 16] during the calculation. This assumption simplifies the governing equation (5) to:

$$\frac{\partial}{\partial z}\left(-\frac{K_z}{\mu}\frac{\partial P}{\partial z}\right) = \frac{1}{V_f}\frac{\partial V_f}{\partial t} \qquad (6)$$

NUMERICAL SIMULATION (Validation & Parametric study)

Firstly, a validation of the numerical resin infusion model is made through the comparison between experimental and numerical results. Then, we perform a parametric study to investigate the influence of processing conditions on the final part thickness and the resin infusion time.

Experimental validation of the numerical infusion model

A numerical validation of the infusion model has been made by an inverse method in Ouahbi et al [17]. The experimental device with the hydro-mechanical coupling HMz is used to validate the resin infusion model. The analyses are performed for two cases of boundary conditions:

- imposed displacement (according to the pre-assigned compaction velocity)
- imposed compaction pressure (σ_z)

The flow can be controlled in injection, with imposed resin pressure (P_i) or with imposed resin flow-rate (Q_i). In this work, the fibrous reinforcement is placed between the two grids of the experimental device (HMz) and the flow is controlled with imposed flow-rate ($Q_0 = 1{,}7.\,10^{-6}\, m^3/s$). Once the steady state is reached, the displacement or the compaction pressure of the experimental device is imposed.

Imposed displacement

The results for compaction pressures by numerical calculation and experimental measurement are compared with each other in the case of imposed displacement, and a good agreement is shown in fig. 2.

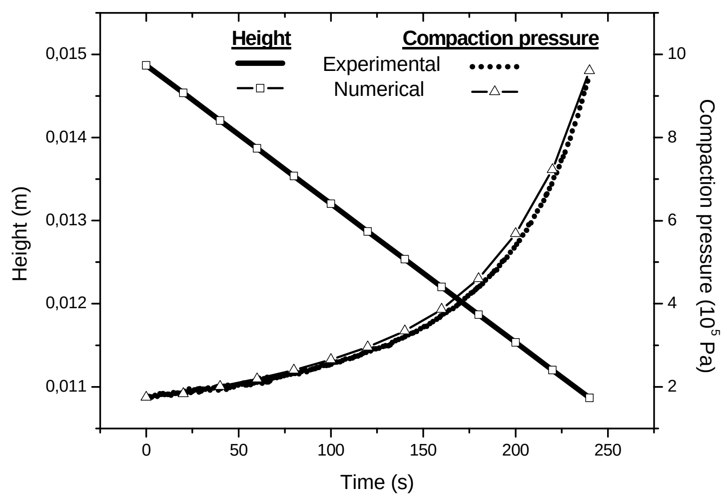

Fig. 2 Comparison of the compaction pressures by numerical calculation and experimental measurement along the time evolution.

Imposed compaction pressure

In this case, we impose a ramp rate of compaction pressure (1kN/min) up to 6 bars and then this compaction pressure is maintained. The comparison between experimental and numerical results for the part height evolution according to time is shown in Fig. 3.

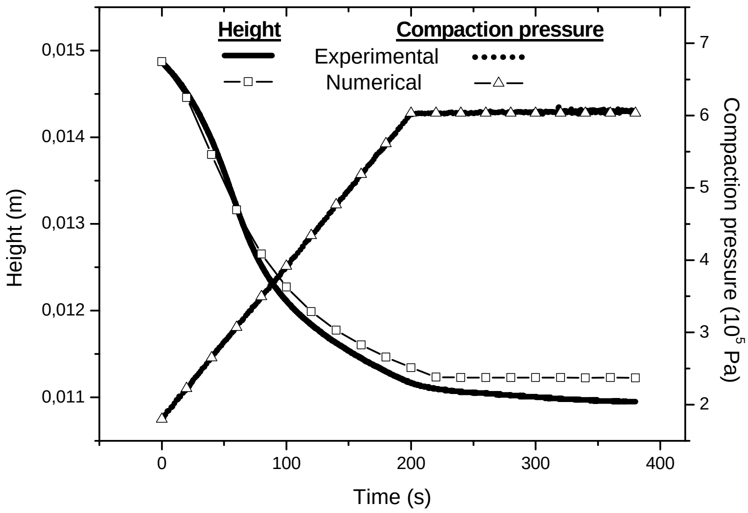

Fig. 3 Comparison of the part heights by numerical calculation and experimental measurement along the time evolution.

Numerical results and parametric study

The numerical prediction for resin infusion process is performed for an initial fibre volume fraction of 40%. The resin temperature is 90°C, the viscosity variation in function of temperature is treated as same way as in [1]. Five different compaction pressures of 1, 2, 3, 4 and 5 (10^5 Pa) are considered. As can be seen in Fig. 4, the infusion height, as expressed in percentage, increases in the course of time.

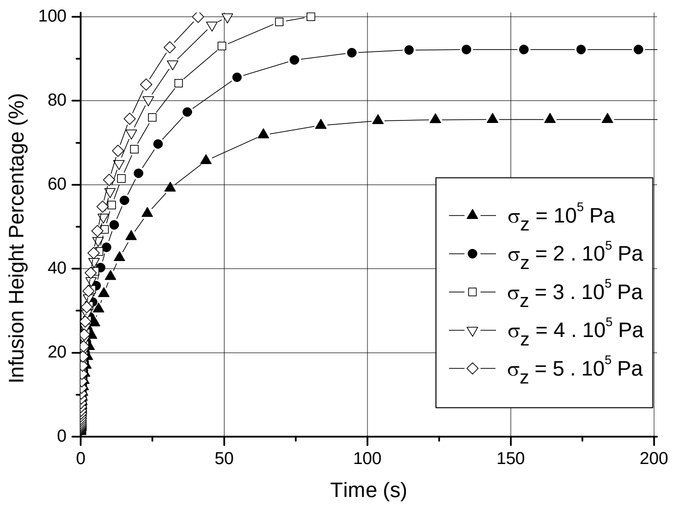

Fig. 4 The time-dependent evolution of the infusion height percentage for different pressure compactions.

Given an initial fibre volume fraction of 40% and a fixed compaction pressure of 200 kPa, four different resin temperatures of 80, 90, 100 and 110 °C are considered (Fig. 5). As can be expected, higher temperature leads to a faster infusion at the beginning of mould filling. However, it also results in a faster curing of resin and the total infusion height was not reached. Lower resin temperature resulted in longer infusion time, but the resin cure reaction is also delayed. As a result, the total infusion height is attained.

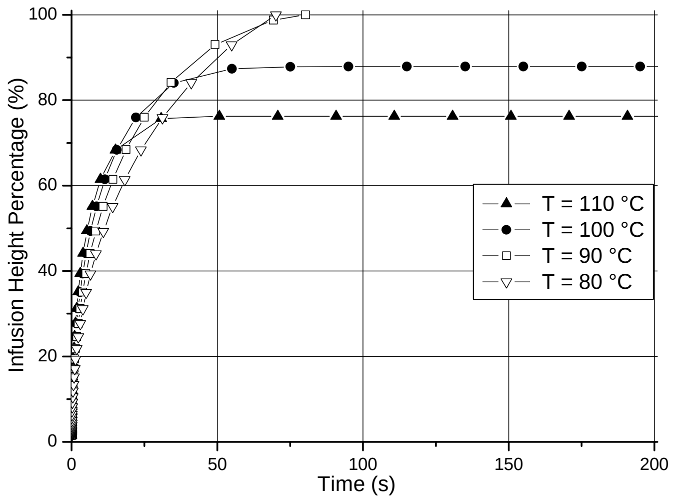

Fig. 5 The time-dependent evolution of the infusion height percentage for different resin temperatures.

The ratio between the initial and the final height of the part in function of compaction pressure was presented in Fig. 6. We also illustrate the relation of the final fibre volume fraction versus compaction pressure.
The final volume fraction of the part increases with the increase in compaction pressure.

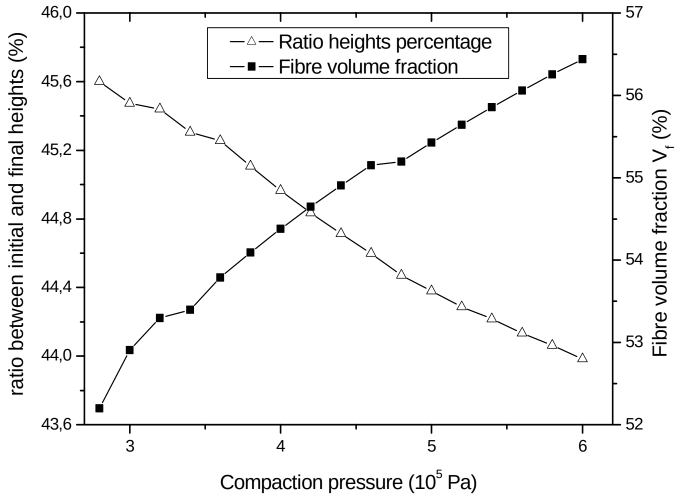

Fig. 6 Representation of the final fibre volume fraction in function of the compaction pressure.

In Fig. 7, a representation of the infusion time in function of the compaction pressure is provided. The infusion time is the time necessary for the resin to completely infuse the part, and it does not include the cure time.

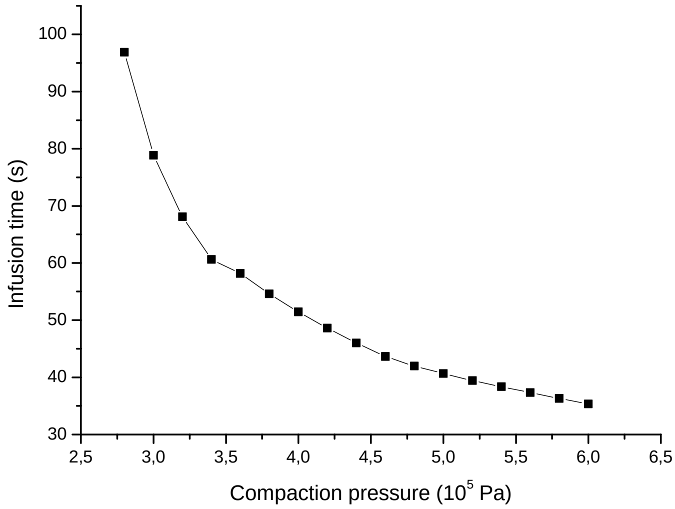

Fig. 7 Representation of the time infusion in function of the compaction pressure.

As seen in Fig.7, the infusion time decreases according to the increase in compaction pressure. Hence, this information can be used to determine the compaction pressure necessary for a total process cycle time to be achieved.

CONCLUSIONS

A numerical modelling of infusion process considering hydro-mechanical coupling and perform deformation was made. An experimental validation of the numerical resin infusion model was made by an experimental device with hydro-mechanical coupling HMz. A comparison between experimental and numerical results was made, and we obtained a good agreement. The infusion height was investigated for different compaction pressures and resin temperatures. The simulation can also be used to predict the resin infusion time and the final fibre volume fraction.

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REFERENCES

1. J. Park, MK. Kang. “A numerical simulation of the resin film infusion process”, *Composite Structures*, Vol. 60, 2003, pp. 431-437.

2. V Antonucci, M. Giordano, L. Nicolais, A. Calabrò, A. Cusano, A. Culoto, S. Inserra. “Resin flow monitoring in the resin film infusion process”, Materials Processing Technology, 143-144, 2003, pp. 687-692.

3. D. Ambrosi and L. Preziosi. “Modelling matrix injection through elastic porous performs”, *Composites Part A: Applied Science and Manufacturing*, Vol. 29, 1998, pp 5-18.

4. I. Sevotianov, VE. Verijenko, CJ. Klemperer. “Mathematical model of cavitation during

resin film infusion process", *Composite Structure,* Vol. 48, 2000, pp. 197-203.

5. DC. Blest, S. McKee, AK. Zulkifle, P. Marshall. "Curing simulation by autoclave resin infusion," *Composite Science and Technology*, Vol. 59, 1999, pp. 2297-2313.

6. AC. Loos, JD. MacRae. "A process simulation model for the manufacture of a blade-stiffened panel by the resin infusion process", *Composite Science and Technology*, Vol. 56, 1996, pp. 273-288.

7. NL. Han, SS. Suh, JM. Yang, HT. Hahn. "Resin film infusion of stitched stiffened composite panels", *Composites Part A: Applied Science and Manufacturing*, Vol. 34, 2003, pp. 227-236.

8. N.C. Correia, F. Robitaille, A.C. Long, C.D. Rudd, S.G. Simacek, S.G. Advani. "Analysis of the vacuum infusion moulding process: I. Analytical formulation", *Composites Part A: Applied Science and Manufacturing*, Vol. 36, 2005, pp. 1645–1656.

9. MA. Biot. "General theory of three dimensional consolidation", *Journal Applied Physics*, Vol. 12, 1946, pp. 155–164.

10. BR. Gebart. "Permeability of unidirectional reinforcements for RTM", *Journal of Composite Materials,* Vol. 26, no.8, 1992, pp. 1101–1133.

11. TG. Gutowski, T. Morigaki, Z. Cai. "The consolidation of laminate composites", *Journal of Composite Materials*, Vol. 21, 1987 pp. 172–88.

12. TG. Gutowski TG, G. Dillon. "The elastic deformation of fiber bundles", In: Gutowski TG, editor. *Advanced composites manufacturing*. Willey; 1997. pp. 138–9.

13. H. Darcy. "Les fontaines publiques de la ville de Dijon" *Dalmont*, Paris, 1856.

14. P. Ouagne et J. Bréard, "Sollicitation HydroMécanique de milieux fibreux en vue de l'optimisation des procédés d'infusion", *14èmes Journées Nationales sur les composites JNC 14*, Compiègne 2005.
.
15. M. Danis, C. Del Borrello, E. Lacoste, O. Mantaux, "Infiltration of fibrous preform by a liquid metal: modelization of the preform deformation", (*ICCM12*), 1999, paper n° 877.

16. E. Lacoste, O. Mantaux, M. Danis. "Numerical simulation of metal matrix composites and polymer matrix composites processing by infiltration : a review", *Composites Part A: Applied Science and Manufacturing*, Vol. 33, 2002, pp. 1605-1614.

17. T. Ouahbi, A. Saouab, P. Ouagne, J. Breard, S. Chatel. "A Simulation Model for the Infusion Process", *The 9th International ESAFORM Conference on Material Forming*, 2006, Paper n° 61.